GEOPHYSICS, VOL. 54, NO. 2 (FEBRUARY 1989); P. 235-244, 18 FIGS.

Mapping and monitoring electrical resistivity with surface and subsurface electrode arrays

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ABSTRACT

Electrical resistivity measurements using combinations of subsurface and surface electrodes are more sensitive to subsurface inhomogeneities than arrays confined to the surface. A further advantage of the subsurface configuration is that the strong influence of near-surface inhomogeneities can be reduced by differencing the measured apparent resistivities with a reference set of values obtained with the subsurface electrode(s) at a particular depth. This process accentuates the response of features near the downhole electrode while canceling the response of the near-surface features.

An idealized two-dimensional model of a nuclear waste repository has been used to demonstrate the effectiveness of this differencing scheme. It is shown that resistivity measurements using borehole electrodes well away from the repository and on the surface are sensitive to changes in the repository that could not be practically observed from surface measurements. This sensitivity is preserved in the presence of a conducting and inhomogeneous surface layer and, most importantly, it is preserved even if the resistivities of the near-surface features also change.

INTRODUCTION

Electrical resistivity methods, like many other geophysical methods, are ideally suited to measure the properties of a region for which it is impossible to gain direct access. Any or all of the electrodes can be placed in the subsurface although, traditionally, surface arrays have been employed. The resulting interpretation of the conductivity distribution is not unique, nor does it provide high resolution of subsurface features. In many applications this latter property is to our advantage, since the measurements yield bulk average values of the conductivity which often include features that are not included in hand samples or borehole logging measurements.

A practical problem that is encountered with all surface configurations of electrodes is that near-surface variations in conductivity have a strong effect on the apparent resistivities for all electrode separations. The strong imprint of the near-surface inhomogeneities often completely obscures the response from deeper parts of the section. Even a homogeneous, conductive overburden layer reduces the sensitivity of surface measurements to underlying bodies.

Resistivity mapping using subsurface electrodes permits far greater accuracy and resolution than can be obtained with surface-only arrays. Using buried current sources, Alfano (1962), Merkel (1971), and Snyder and Merkel (1973) developed solutions for the potential distribution on the surface of a layered medium, while Merkel and Alexander (1971) analyzed the subsurface resistivity response of spherical models in a half-space. Barnett (1972) developed surface integral equation solutions for arbitrarily shaped two-dimensional (2-D) and three-dimensional (3-D) bodies set in a homogeneous half-space, and Daniels (1977, 1978) discussed in detail anomalies due to spherical bodies and for an n-layered earth for the crosshole and borehole-to-surface array configurations. Dey and Morrison (1979) compared downhole and surface current electrode configurations using a general 3-D numerical modeling algorithm. Field applications of these techniques were presented in Daniels and Scott (1980, 1981), Daniels (1983), and Daniels and Dyck (1984). Theoretical solutions for apparent resistivity anomalies due to spheres and oblate and prolate spheroids were discussed in Dobecki (1980), Lytle (1982), and Lytle and Hanson (1983). Wilt et al. (1983) used the 3-D program developed by Dey and Morrison (1979) to model an idealized geothermal reinjection process, and later Wilt and Tsang (1985) used the same program to simulate subsurface contaminant migration. Yang and Ward (1985a, b) and Beasley and Ward (1986), using integral-equation techniques, presented the results of sensitivity analyses of thin ellipsoids, spheroids, and plate-like bodies (simulating fracture zones) from single-hole and crosshole arrays. Similarly, Eloranta

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(1985, 1986) compared borehole-to-surface pole-pole and pole-dipole configurations over 3-D bodies and, using integral-equation solutions, considered the effects of vertical contacts on mise-à-la-masse anomalies. Bowker (1987) used combined numerical (integral-equation) and analytical solutions to look at mise-à-la-masse anomalies from slab-like and disk-like bodies, while Poirmeur and Vasseur (1988) developed an integral-equation solution program to model borehole-to-surface and crosshole arrays and presented a new plotting convention to help interpret hole-to-hole resistivity survey data. All these studies demonstrated the intuitively expected result that subsurface features are more easily detected if some or all of the electrodes are placed in the subsurface.

Except in the study by Zhao et al. (1986), the problems of near-surface variations and subsurface geologic noise were not addressed. It was expected that measurements along the surface would be sensitive to near-surface variations whether some of the electrodes were in the subsurface or not. Zhao et al. (1986) found that to achieve a reasonable mean-square error (between models with and without geologic noise), the modeled cross-borehole resistivity data had to be normalized by the apparent resistivity of the half-space calculated without a target at each pole location. Difficulties arose in trying to use their normalization procedure to detect a thin conductive body in a layered earth or near a contact without knowing a priori the background resistivity structure. Detecting the target in the presence of buried topography or conductive overburden also proved difficult.

Borehole-to-surface modeling

The 2-D and 3-D codes of Dey (1976) and Dey and Morrison (1976, 1979) have been modified to permit analyses of the responses of hole-to-surface and crosshole electrode arrays to arbitrarily shaped resistivity inhomogeneities. The programs have been used to study the ability of such arrays to map, or detect changes in, the subsurface resistivity distribution in the presence of conductive overburden or near-surface inhomogeneities. Measuring changes in subsurface resistivity should be useful for monitoring processes such as contaminant migration, steam flooding in enhanced oil recovery, and geothermal production, and for determining the integrity of a mined geologic repository for nuclear waste. By differencing the observed apparent resistivities with those obtained at a particular depth of interest, surface effects can be greatly reduced. Thus, in addition to the increased response that is achieved with subsurface electrodes, the most important attribute of such arrays is the reduction, and often elimination, of the near-surface effects.

To illustrate the power of subsurface-surface arrays, an idealized 2-D model of a waste storage repository has been used to investigate the responses from conventional surface dipole-dipole and borehole-to-surface arrays. This study consisted of comparing the sensitivity of dipole-dipole arrays to the repository itself and to small changes occurring over time in the repository, and, finally, to finding ways to handle surface effects (which might also vary with time).

When electrodes can be placed in the subsurface, the number of possible or practical array configurations becomes truly formidable. Transmitter-receiver combinations such as pole-pole, pole-dipole, and dipole-dipole (some with the practical variable of dipole length), combined with surface-surface, surface-to-borehole, and borehole-to-borehole configurations soon result in overwhelming catalogs of the familiar type curves or pseudosections. This paper does not attempt to analyze the relative effectiveness of different arrays for investigating the subsurface. That analysis must wait until an objective inversion scheme, which can be used to compare array responses for different classes of inhomogeneities, is developed. Rather, this study has focused on extending a common array (dipole-dipole) to the subsurface and showing that, with a simple differencing scheme, the effects of surface inhomogeneities can be greatly reduced.

The waste repository model has been chosen as an example because the siting and integrity of these repositories is a challenging national problem in which all the geosciences are heavily used. Geophysics can play a major role in site characterization and in monitoring the subsequent performance of the repositories. In particular, the predictions of site performance depend critically on the local groundwater regime because in the event of rupture of the radioactive containers, the contaminants would be transported to the accessible environment principally by solute transport by groundwater.

The detailed sequence of events from a hydrologic point of view may be quite compex. After excavation, the repository will be at atmospheric pressure and the groundwater will drain into the repository, unsaturating the surroundings. After emplacement of the waste, the temperature of the repository will rise to, or perhaps exceed, the boiling point. After backfilling and closure, the repository will begin to resaturate, at which point the balance between thermal input, groundwater saturation, and thermal conductivity will dictate whether a steam front will exist and where it will be located. Since direct measurements would violate the integrity of the repository, it is imperative that means be found to monitor this process to be sure that the models used to predict the performance are valid.

Electrical resistivity is a particularly promising parameter to measure for monitoring this aspect of repository performance, since the electrical resistivity depends so heavily on saturation and temperature. Resistivity methods, as with many other geophysical methods, are also ideally suited because the measurement can be made away from the repository itself and, once electrodes are emplaced, repeat measurements over even long periods of time are straightforward and accurate.

MODELING RESULTS

Mapping the repository

A data plotting convention and the modeling scheme are illustrated for the simple model (shown in Figure 1) of a hypothetical repository zone represented by a 2-D rectangular region in a uniform half-space. It has been assumed that in excavating and preparing the repository the water content of the rocks has been reduced so that the effective resistivity of a zone two units thick and three units wide has increased by a factor of two over the background 50 $\Omega \cdot$m half-space. The choice of background resistivity is arbitrary and is not intended to represent any particular site. A study by Morrison et al.

(1988) used a background resistivity of 200 Ω · m, which would have been representative of the intended basalt site at Hanford, Washington. The conclusions were the same as those shown here.

The results of a standard dipole-dipole surface survey are presented for this model in Figure 2. The anomaly produced by the repository is small with apparent resistivity variations of less than 2 percent over the background resistivity. Surface surveys, however, are usually strongly affected by near-surface variations in resistivity, and this has been simulated with the two surface conductors of 25 Ω · m shown in Figure 3. From a practical point of view, the surface conductors imprint a dominant pattern on the pseudosection and completely mask the repository anomaly.

Resolution of the repository is greatly improved using borehole current sources and surface receiver dipoles as shown in

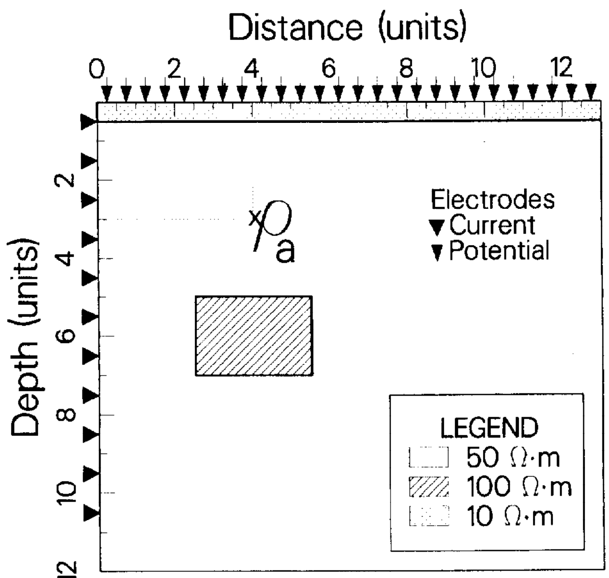

FIG. 1. Idealized model of a nuclear waste repository underlying a thin conductive layer. The arrows represent electrode locations on the surface and in the borehole. The symbol ρ_a illustrates the plotting convention for apparent resistivities measured with the borehole-to-surface configuration. ρ_a is associated with the current dipole centered at three units depth and the surface potential dipole centered four units out from the borehole. The corner legends in all the figures associate the modeled resistivity distribution with shaded zones.

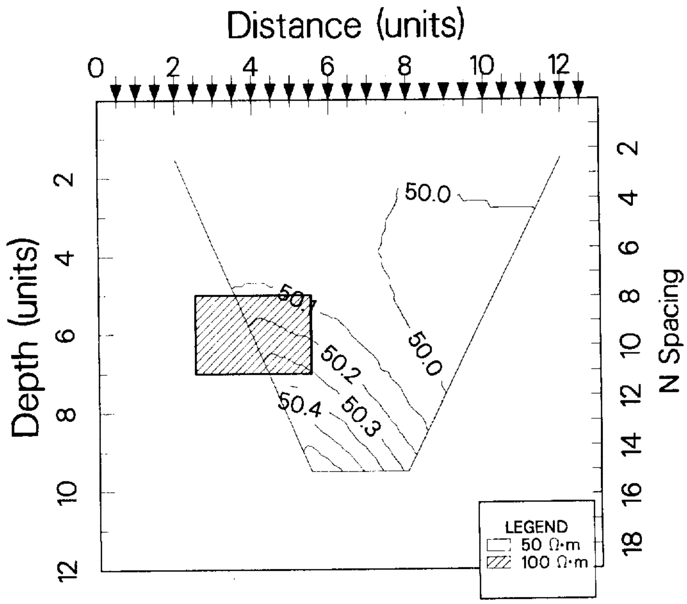

FIG. 2. Surface dipole-dipole apparent resistivity pseudosection for the whole repository model within the half-space. Contours are in intervals of 0.1 Ω · m.

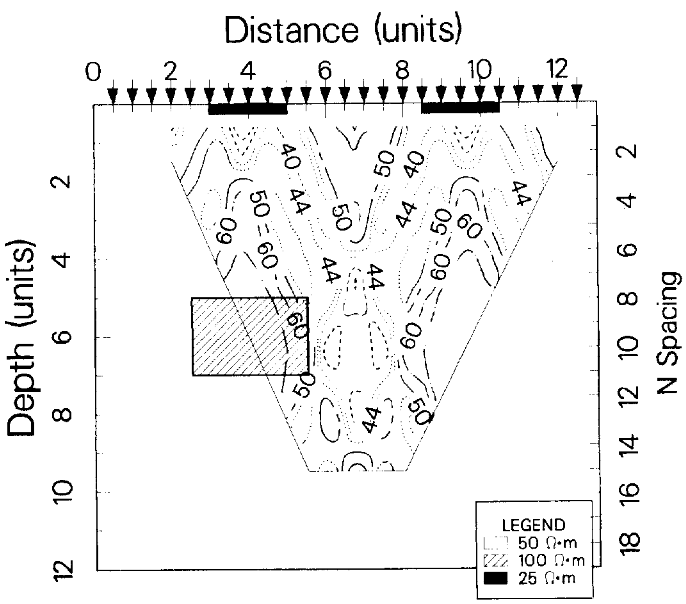

FIG. 3. Effects of near-surface conductors on surface dipole-dipole apparent resistivity data. The contour values are semi-logarithmic in ohm-meters.

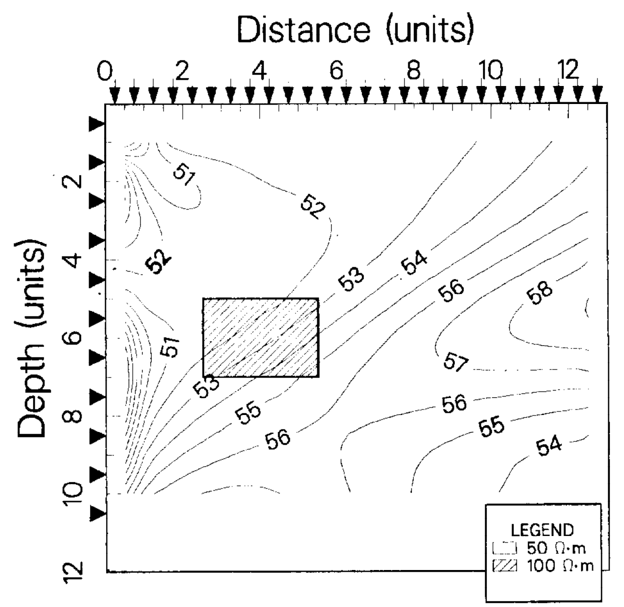

FIG. 4. Borehole apparent resistivity data using dipole current sources for the whole repository model. Contours are in intervals of 1.0 Ω · m.

Figure 4 by the subsurface apparent resistivity pseudosection for the waste repository model. In this study the current electrodes are placed vertically with unit separation starting at 0.5 units and are treated as a series of dipole sources. The apparent resistivity measured for a given depth of the current dipole and location of surface potential electrodes is plotted vertically midway between the current electrodes and horizontally midway beneath the potential electrodes. A representative apparent resistivity ρ_a plotted with this convention is shown in Figure 1. Plotted midway between the current dipole with electrodes at 2.5 and 3.5 units depth, ρ_a is plotted at three units depth and laterally at four units (plotted midway between the potential dipole with electrodes at 3.75 and 4.25 units).

Unlike the normal surface dipole-dipole array pseudosection, this plotting convention actually has a true depth axis and has some connection to the true geologic section. For example, if the borehole electrode traverses a layer, the boundaries, in apparent resistivity, occur at exactly the depth of the layer (as they do in conventional electric logging). Similarly, surface effects show up at the correct horizontal location. Features within the subsurface have an indirect expression in the pseudosection, just as they have for surface arrays. The convention used here is essential to keep the features encountered on the surface or in the borehole in their correct locations.

To draw attention to the perturbation caused by the repository, it is informative to plot the results as differences from some background level. Since it may be difficult to determine the background or half-space resistivity in practice (see Zhao et al., 1986), the results are presented as percentage differences taken with respect to the apparent resistivities observed at a particular depth of the current dipole source. The resulting percent difference pseudosections should be indicative of the differences in the conductivity distribution relative to the chosen depth of interest.

Percent difference is defined here as $[(\rho_2 - \rho_1)/\rho_1] \times 100$, where ρ_1 is the apparent resistivity measured at the particular depth which is used as the reference in each calculation and ρ_2 is the resistivity located at the same horizontal position as ρ_1 but measured at different source depths.

The pseudosection in Figure 5 is obtained using this scheme for the repository model. All the apparent resistivities in the section are compared to the values observed with the current dipole source centered at six units depth, the approximate depth of the waste repository.

The percentage difference pseudosection in Figure 5 shows variations from -8.0 percent to $+8.0$ percent, an order of magnitude greater than the percentage variations seen in the pseudosection for the surface dipole-dipole array shown in Figure 3. This larger variation is due in part to the fact that the subsurface current electrodes, at the level of the repository, are twice as close to the repository as are the surface electrodes, but the variation exists primarily because the current sources are in the medium with the target. This is basically the same conclusion reached by the many studies referenced above.

It should also be noted from Figures 4 and 5 that the greatest anomalies occur when the current sources are below the level of the target body. Therefore, in order to maximize the effectiveness of borehole-to-surface resistivity measurements, borehole resistivity surveys must extend below the target. This requirement effectively means drilling deeper than the target

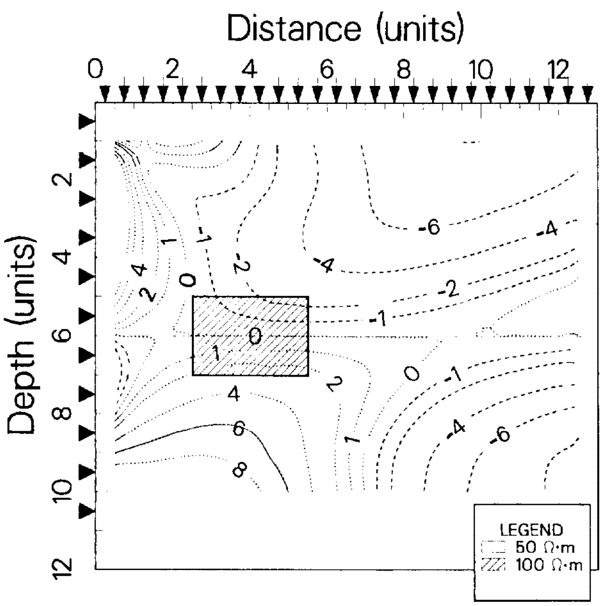

FIG. 5. Percentage difference pseudosection for the data in Figure 4 referenced to the apparent resistivities obtained with the current dipole centered at six units depth. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

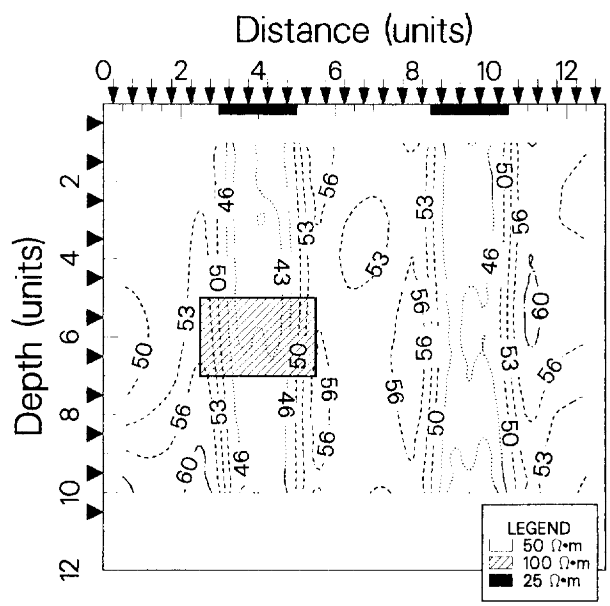

FIG. 6. Effects of near-surface conductors on borehole apparent resistivity data using dipole current sources. The contour values are semilogarithmic in ohm-meters.

itself. How much deeper depends on the distances between the target and the boreholes used in the subsurface surveys as well as on target size, shape, and the conductivity contrast with the surrounding geology.

Removing surface effects

Subsurface arrays, by differencing data at depth, reduce near-surface effects that usually confound quantitative interpretation of surface surveys. For the model of the repository which includes surface conductors, the apparent resistivity pseudosection, from using subsurface dipoles, is shown in Figure 6. Compared to the data in Figure 4, these data are dominated by surface effects. However, the percent difference data, relative to the apparent resistivities measured at six units depth, shows in Figure 7 that the effects due to the surface conductors have been considerably reduced. In fact, Figures 5 (the case in which no surface conductors were present) and 7 exhibit similar patterns, especially for current electrodes below the repository level. The pseudosection plot in Figure 8, which was produced by subtracting the data in Figure 7 from those in Figure 5, clearly shows that the two data sets are very similar in the vicinity of the repository in the pseudosection.

The reason for this rather surprising result lies in the fact that the potential distribution near the surface is not much affected by changes in the source position if the source is relatively "far" away. Thus, the differencing of apparent resistivities measured on the surface from two source positions at depth would be small in the absence of the deep feature (in this case the repository). However, if a feature is introduced close to the source, then the pattern of potential distribution changes significantly for changes in source position. Differencing now accentuates the feature at depth. This is a unique feature of measurements made with subsurface electrodes that can not be realized with surface arrays. The technique similarly lessens topographic effects.

This important aspect of subsurface-to-surface arrays has been illustrated with a very simple model. A more realistic model might be one in which a conductive surface layer is also present. Such a model and the accompanying apparent resistivity pseudosection for a surface dipole-dipole array are shown in Figure 9. The conductive layer exerts such a strong masking effect that there is no visible sign of the repository in the pseudosection. Analysis of the numerical results showed that the repository caused a maximum of 0.5 percent deviation from the layer response. Such a feature would be undetectable in surface surveys, especially considering the inevitable surface effects.

The pseudosection for borehole dipole sources is shown in Figure 10 for the layered model alone, and in Figure 11 for the layer plus the repository. While the layer response dominates the pseudosection, the perturbation caused by the repository is at least visible. The percent difference pseudosections, referenced to the data at six units depth, for the layered model and the layered model with the repository are shown in Figures 12 and 13, respectively. The presentation accentuates the differences introduced by the repository. Figure 14 is a pseudosection of these differences. It is important to note that the repository introduces perturbations of up to 10 percent over the background layer model apparent resistivities for the

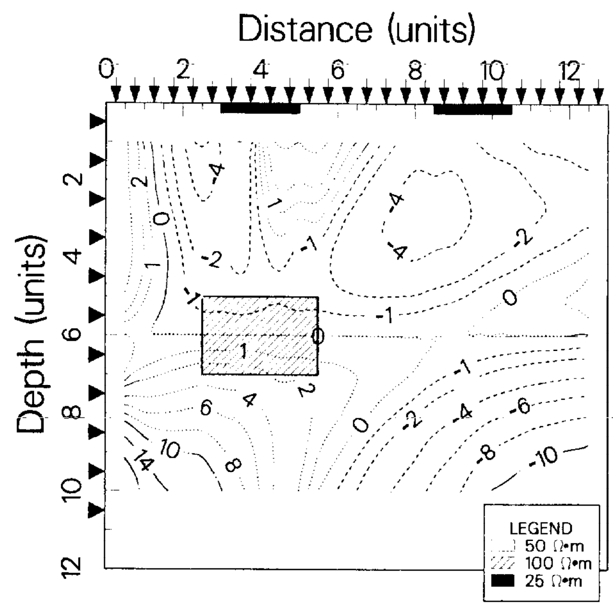

FIG. 7. Percentage differences for the data in Figure 6 referenced to the apparent resistivities obtained with the current dipole at six units depth. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

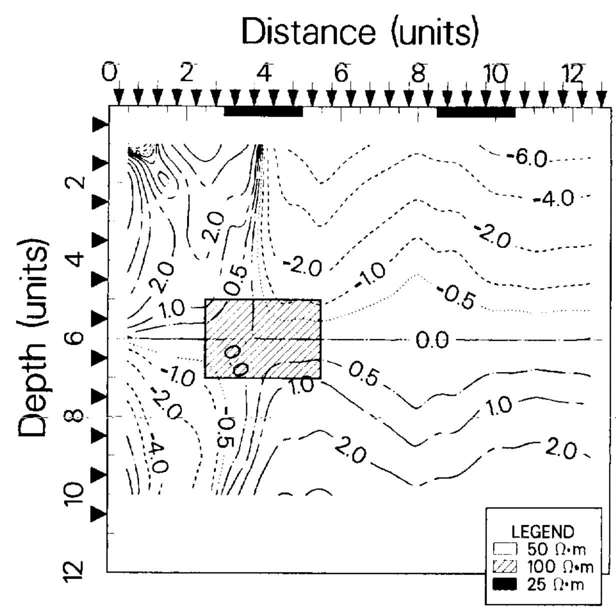

FIG. 8. Illustration of the removal of near-surface effects from resistivity data. The pseudosection results from the subtraction of the percent difference data in Figure 7 from the difference data in Figure 5. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

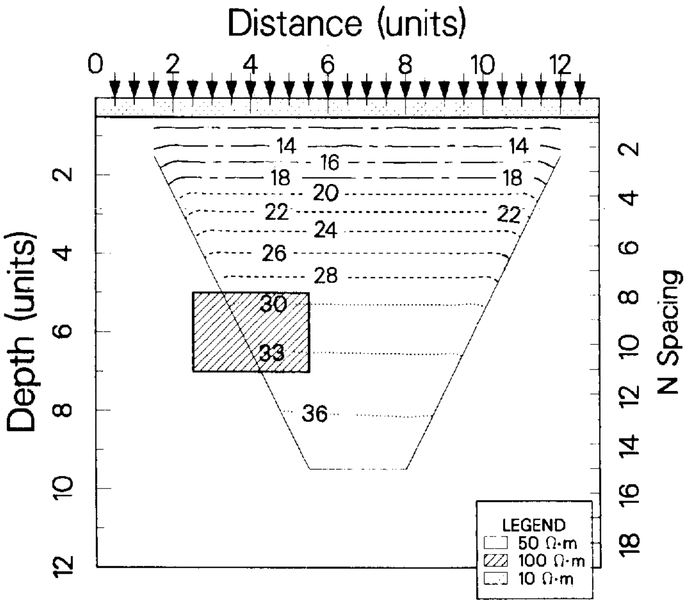

FIG. 9. Surface dipole-dipole apparent resistivity pseudosection for the whole repository model including the conducting surface layer. Note the lack of sensitivity of this array to the presence of the repository. The contour values are semilogarithmic in ohm-meters.

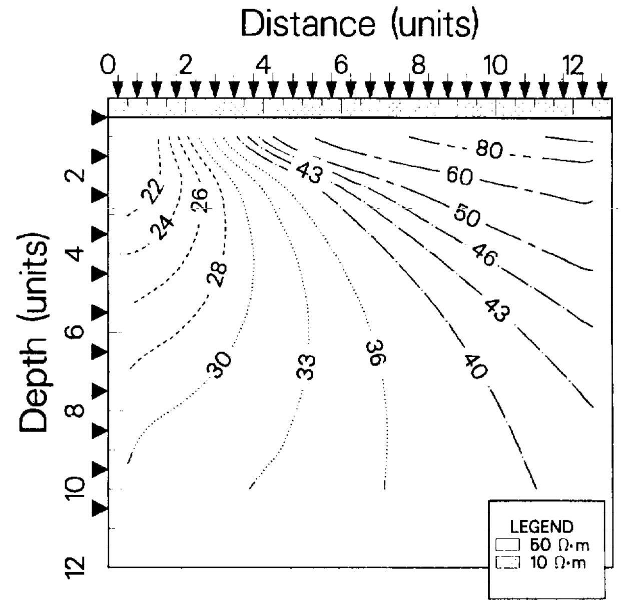

FIG. 10. Borehole apparent resistivity data using dipole current sources for the conductive layer over the half-space model. Contours are in semilogarithmic intervals in ohm-meters.

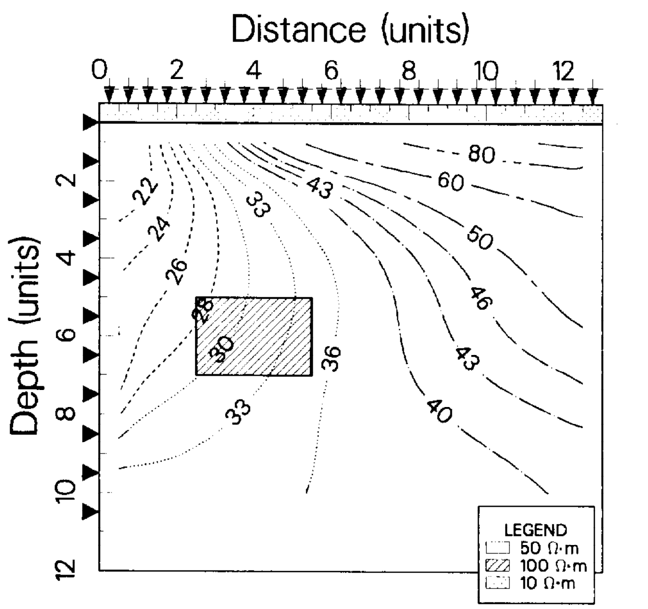

FIG. 11. Borehole apparent resistivity data using dipole current sources for the whole repository in the presence of the conductive layer. Contours are in semilogarithmic intervals in ohm-meters.

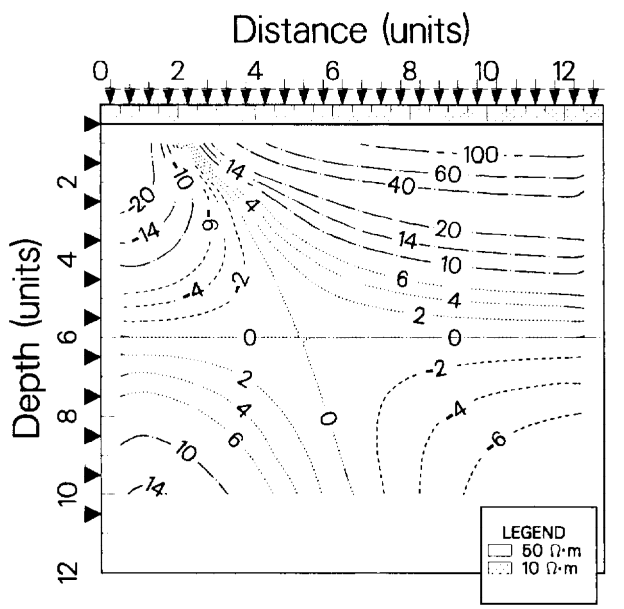

FIG. 12. Percentage difference pseudosection for the layer over the half-space model (Figure 10). The data are compared to the apparent resistivities obtained with the current dipole centered at six units depth. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

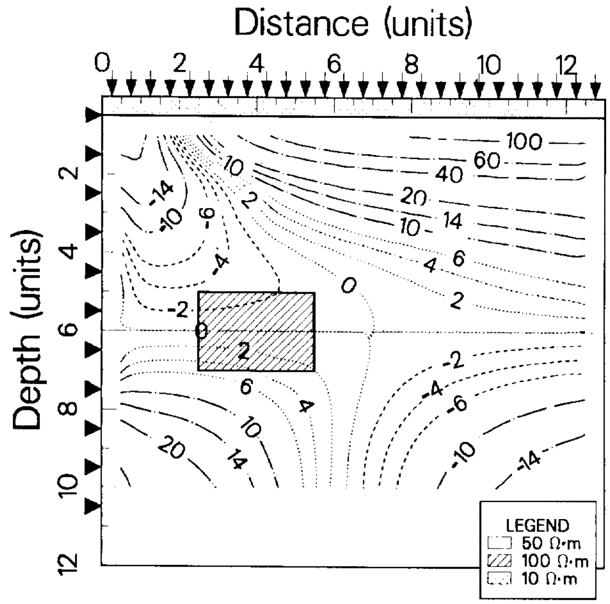

FIG. 13. Percentage difference pseudosection for the model in Figure 11 referenced against the apparent resistivities obtained with the current dipole centered at six units depth. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

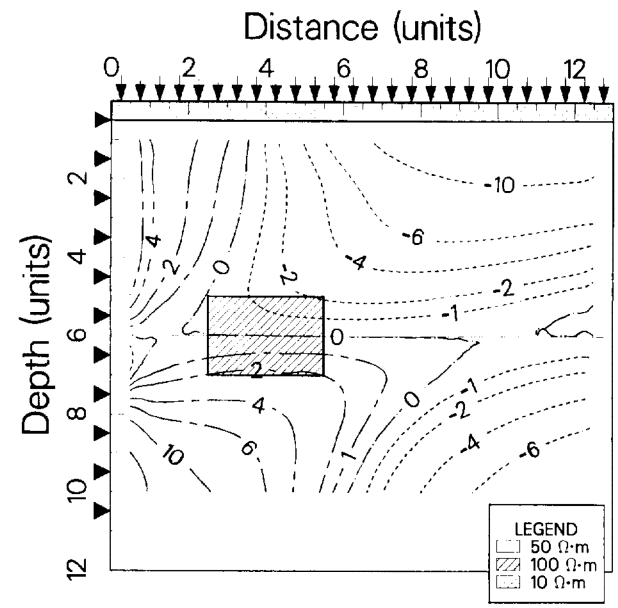

FIG. 14. Illustration of the removal of the conductive layer effects from the borehole resistivity data. The pseudosection results from the subtraction of the percent difference data in Figure 12 from the difference data in Figure 13. Note the similarities of this figure, except quite near the surface, to Figure 5 (the model with the repository alone in the half-space). The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

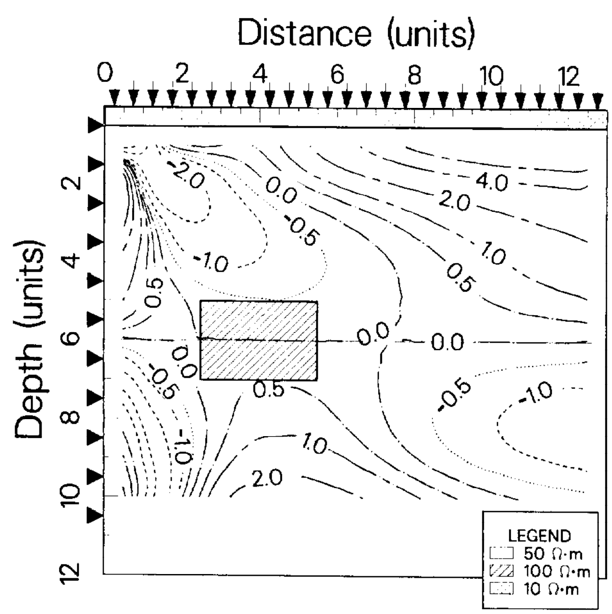

FIG. 15. This pseudosection, resulting from the subtraction of the percent difference data in Figure 14 from the difference data in Figure 5, illustrates the effective removal of the conductive surface layer from the borehole resistivity data. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

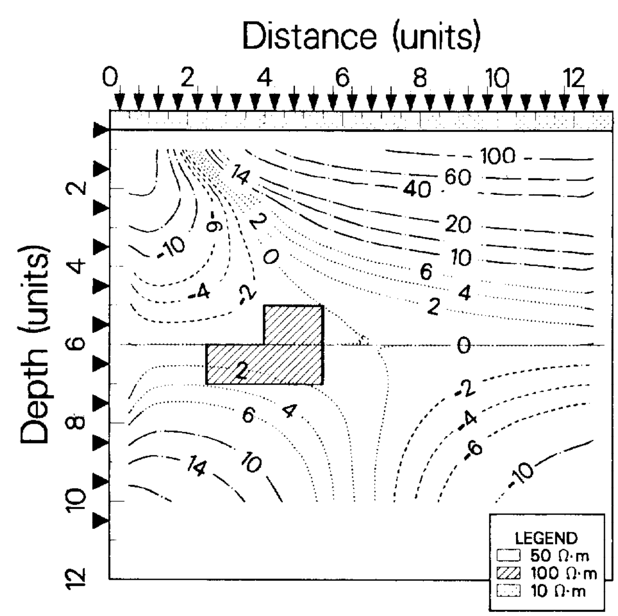

FIG. 16. Pseudosection illustrating the mapping sensitivity of the percent difference method to the partially resaturated repository model in the presence of the conductive surface layer. The apparent resistivities are referenced against the values observed with the current dipole centered at six units depth. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

subsurface-to-surface array. The maximum perturbation for the surface dipole-dipole array was 0.5 percent.

It is also instructive to compare the subsurface-to-surface pseudosection for the model with no surface layer (Figure 5) to Figure 14, which shows the difference between the pseudosections for the layered case with and without the repository. If the repository were completely uncoupled from the layer, these two pseudosections should be identical. The actual differences are shown in the pseudosection of Figure 15: it is seen that there are discrepancies of up to 4.0 percent in the upper right quadrant. However, in that part of the pseudosection where the repository manifests itself most clearly, the differences are less than 1.0 percent. This observation has important consequences when subsurface arrays are considered for time monitoring of changes in the resistivity of the subsurface. The results shown in Figure 14, for example, would have been obtained from differencing the pseudosections taken before and after excavation of the repository (provided the surface layer did not change in resistivity during the same time interval—a possibility to be discussed below).

In summary, the subsurface-to-surface configuration, coupled with the concept of differencing apparent resistivities with the values at a particular depth of interest, accentuates the effect of the repository model studied here even in the presence of a high-conductance surface layer. While the surface layer might make absolute determination of the dimensions and resistivity of the repository difficult, monitoring changes in a (known) repository become eminently feasible with such methods. Both detection and time monitoring would be impractical using arrays confined to the surface.

Monitoring changes in the repository

To complete this analysis, several more models were introduced to investigate the effectiveness of the subsurface-to-surface arrays and of differencing in detecting changes in the repository model in the presence of time changes in the surface conductors brought about by rainfall or changes in the groundwater level.

Figure 16 shows a 2-D model in which partial resaturation has occurred; i.e., the upper left quadrant of the waste repository has reverted back to 50 $\Omega \cdot m$, the half-space resistivity. As in Figure 13, the apparent resistivities in this percentage difference pseudosection have been compared to the values observed with the current dipole centered at six units depth. The patterns in Figures 13 and 16, while similar, are different enough that one could determine that some change had occurred in the vicinity of the repository.

In a true time monitoring experiment, one could subtract the percentage difference values calculated for the partially resaturated model (Figure 16) from those calculated for the whole repository model (Figure 13). This results in the time-differenced pseudosection shown in Figure 17. All the infor-

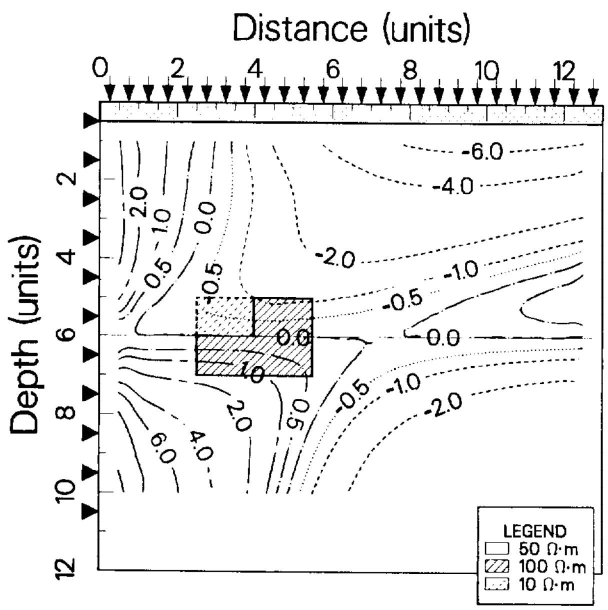

FIG. 17. Pseudosection illustrating the monitoring sensitivity of the percent difference method. The percent difference data in Figure 16 (the partially resaturated repository model) have been subtracted from the percent difference data in Figure 13 (the whole repository model). The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

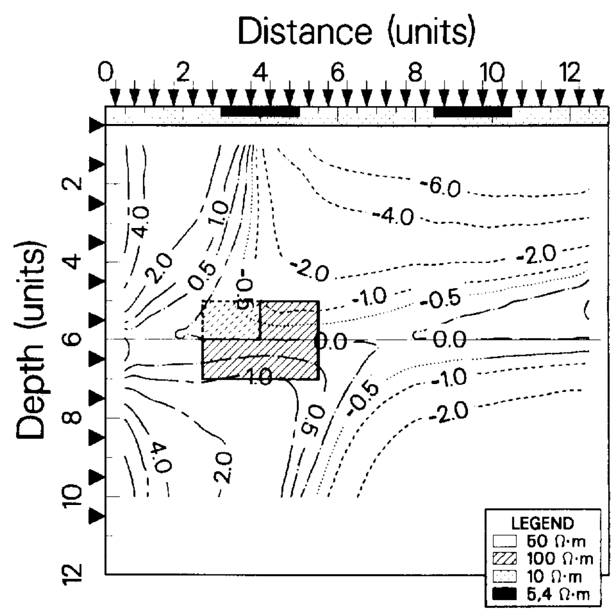

FIG. 18. Borehole dipole source pseudosection illustrating the worst case scenario in which both the surface and subsurface resistivity distributions have changed from one period of measurement to the next. This plot shows the difference between the percent difference data (referenced against the six unit depth) for a whole repository model with 5 $\Omega \cdot m$ near-surface conductors and a partially resaturated model with 4 $\Omega \cdot m$ bodies (a change of 20 percent). Note the similarities with Figure 17. The chain-dotted line at six units depth represents the zero datum. Contours are in semilogarithmic intervals in percent.

mation in Figure 17 is directly related to only the differences between the whole and partially resaturated models. The difference values are all well within our measurement capability of 0.1 percent precision and are indicative of the changes which took place in the repository zone.

Time-varying surface effects and partial resaturation

Finally, a model has been studied in which conductors embedded in the surface layer are changed from 5 $\Omega \cdot m$ to 4 $\Omega \cdot m$ during the time that the repository partially resaturated. The time-differenced pseudosection is shown in Figure 18. Since Figures 17 and 18 are almost identical, it is clear that such an experiment, using apparent resistivities referenced to the repository depth, is essentially independent of changes in the near-surface inhomogeneities. The influence of the changing surface conductors shows up in discrepancies of a few percent in the bottom left and upper right corners of the pseudosection.

The variations assigned to the surface inhomogeneities are probably realistic but little is known about time changes in surface layers. Morrison and Fernandez (1986) ascribed observed changes in apparent resistivity in a large-scale dipole-dipole survey to near-surface changes of 20 percent in intrinsic resistivity. Qian (1976) observed changes in apparent resistivity of 14 percent over a few years using Wenner configurations which sensed the upper few hundred meters. In any real implementation of this scheme for repository monitoring, it would be prudent to monitor near-surface variations with a concurrent surface dipole-dipole survey.

This technique also works well with surface arrays in which the resistivities of the near-surface conductors have *not* changed over time. The near-surface effects which were dominant in the surface dipole-dipole data observed in Figure 3 can be reduced by comparing (as in Figure 18) the percent difference data calculated relative to the background half-space at the two different times. The surface conductors affect the survey data the same way at each time and can be eliminated through the percentage difference calculation.

DISCUSSION AND CONCLUSIONS

The important result of this study is that the usually strong effects of near-surface conductors on subsurface-to-surface arrays are greatly reduced if the apparent resistivities are differenced with respect to the values at the depth of interest. This rather simple procedure is only effective if the target, in this case a nuclear waste repository, is "deep" and sufficiently removed from the surface conductors to be uncoupled from them. Decoupling appears to be quite valid for discrete surface conductors but somewhat less so for a conducting surface layer.

From a different point of view, the near-surface effects drop out of the differenced data because the potentials on the surface near the inhomogeneities have roughly the same geometric pattern for all electrodes past some critical depth. These potentials, normalized by distance and current source (i.e., the apparent resistivities), are all of similar magnitude for current sources at the depths of the target or zone of interest. When the values from two such depths are differenced, the result is near zero. However, if the target is present, the potentials at the surface are very much altered by the distortion of the fields near the source so the differences are produced mainly by the target.

The choice of which current source depth to use as the reference point for studying the apparent resistivity data is arbitrary, since the percent difference pseudosections obtained by using the apparent resistivities from any of the source depths as reference values contain the same information about the resistivity distribution in the surveyed section.

The enhancement of anomalies using subsurface-to-surface arrays, coupled with the differencing scheme to reduce surface effects, shows that such arrays are very sensitive to time changes in a subsurface target zone. The repository model used here would simply be undetectable beneath a surface conducting layer with simple inhomogeneities; furthermore, changes in the model could not be detected with practical levels of measurement precision (0.1 percent). The same model produces changes of ± 10 percent in the subsurface-to-surface pseudosection differenced with respect to the repository depth. A change in the repository, modeled by allowing a quadrant of the repository cross-section to resaturate, also produces changes of ± 6 percent, which indicates a very high sensitivity in the difference pseudosection to small changes in the repository. Finally, this last result has been shown to be little affected if a near-surface conductor changes in resistivity during the same time that the repository changes.

There may be limitations to the effectiveness of this differencing scheme if the geologic model is more complex than the one used here. Complex coupling effects may arise if the target is close to a subsurface boundary such as a vertical contact or some other large feature. Perhaps the most important conclusion from this paper is that the concept of differencing can be very useful in diminishing unwanted signals. Other differencing schemes may be developed for more complicated models, especially if more boreholes are available.

This study focused on a general model of an underground nuclear waste repository. It should be noted that the methods described here are equally applicable to any study of subsurface processes where the electrical resistivity is known to change. Steam, water, or chemical flooding for enhanced oil recovery, geothermal reservoir production, groundwater contamination, or in-situ mining methods are all processes which could be monitored successfully with subsurface resistivity methods.

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